Raytheon

Air Traffic Management System Development and Integration (ATMSDI)

CTOD-2.3-2
Draft Guidelines
Subtask 5 – Simulation Requirements

December 2001

Contract No.: NAS2-00015

Prepared for

NASA Ames Research Center
Richard Mogford, Ph.D.

Prepared by

Raytheon ATMSDI Team
Parimal Kopardekar, Ph.D. and Nicole Sacco, and Kevin Carmen (Titan Systems)

ACKNOWLEDGEMENT

The authors sincerely thank Dr. Richard Mogford for providing ideas and literature, and encouraging discussions.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

EXECUTIVE SUMMARY

Simulation is an important method in assessing benefits and feasibility of advanced concepts such as Distributed Air-Ground Traffic Management (DAG-TM). It is recognized that the fidelity of different simulators, facilities, and fast-time modeling techniques need to be clearly understood for their usage. The end-to-end human-in-the-loop simulation can be expensive. Therefore, it must not be used too early in the concept development stage. However, fast-time simulations, rapid prototyping, part-task simulations, and demonstrations could be used to gather some much needed preliminary data.

These initial guidelines describe various National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA) facilities, capabilities, simulators, and modeling tools that could be used for DAG-TM concept explorations. The guidelines also identify the potential role of these simulation capabilities across different Technology Readiness Levels (TRLs). These guidelines will be updated in the 2002 and 2003 fiscal years as the DAG-TM concepts mature and additional simulation and modeling capabilities are developed.

This Page Intentionally Left Blank

1. BACKGROUND

Simulation provides a cost-effective and low-risk approach to ensure that the advanced concepts such as Distributed Air-Ground Traffic Management (DAG-TM) are both feasible and beneficial. Since the DAG-TM concepts offer a significant shift in roles and responsibilities as compared with current traffic management practices, it is imperative that these concepts be validated. The process of validation will ensure that the concept elements (CEs) are complete and necessary for accomplishing the traffic management activities. Therefore, a number of simulation studies must be performed to ensure the validity of these concepts. It is recognized that not all studies, particularly early stages of Technology Readiness Levels (TRLs), could afford the luxury of end-to-end real-time (RT) human-in-the-loop simulation (HITL) due to its expensive nature. Therefore, both fast-time and RT HITL need to be used for exploration of concepts. It is also recognized that NASA and the FAA have a number of simulation facilities and simulators currently in place. Therefore, these guidelines describe simulation facilities and techniques that can be used for validation studies across different TRLs. The guidelines also identify additional capabilities that are necessary. The guidelines further recommend a method to assess simulator fidelity for a particular validation study.

2. SCOPE

This draft Subtask 5 guidelines document focuses on simulation requirements particularly for DAG-TM CE 5, *En Route Free Maneuvering,* and CE 11*, Terminal Arrival/Self-Spacing for Merging and In-trail Separation.* The simulation capability requirements discussed here may also apply to other CEs.

3. OBJECTIVE

The guidelines document recommends existing simulation capabilities available to conduct research related to DAG-TM. It describes different simulators, models, and facilities that can be used to conduct studies involving all or any of the air traffic control (ATC), flight deck (FD), airline operations center (AOC), and traffic flow management (TFM) functionality. It identifies the gaps where the simulators and capabilities need further development for conducting CE 5 and CE 11 related simulation studies. It also addresses the fidelity of existing simulators and maps their potential use across TRLs.

These guidelines are based on a literature review, author expertise, and discussions with researchers, human factors specialists, engineers, and subject matter experts. A detailed literature review related to fast-time simulation and modeling tools, NASA and FAA simulation facilities, and simulation fidelity assessment techniques was conducted. This literature review was specific to air traffic management operations. The detailed review is provided in the Appendix A.

Sections 4 and 5 describe DAG-TM CE 5 (En Route Free Maneuvering) and CE 11 (Terminal Self-spacing). These descriptions are taken from the DAG-TM concept definition documents developed by NASA Ames Research Center (NASA AATT, 1999).

4. DESCRIPTION OF CE 5: EN ROUTE: FREE MANEUVERING FOR USER-PREFERRED SEPARATION ASSURANCE AND LOCAL TFM CONFORMANCE

This concept element applies to all flight phases (Departure, Cruise and Arrival) in the operational domain of en route airspace.

4.1 CURRENT PROBLEM

(a) ATSP often responds to potential traffic separation conflicts by issuing trajectory deviations that are excessive or not preferred by users.

In the current ATC system, trajectory prediction uncertainty leads to excessive ATC deviations for separation assurance. Due to workload limitations, controllers often compensate for this uncertainty (which may be equivalent to or greater than the minimum separation standard) by adding large separation buffers for conflict detection and resolution (CD&R). Although these buffers reduce the rate of missed alerts, some aircraft experience unnecessary deviations from their preferred trajectories due to the unnecessary "resolution" of false alarms (i.e., predicted "conflicts" that would not have materialized had the aircraft continued along their original trajectories). In those cases where a potential conflict really does exist, the buffers lead to conservative resolution maneuvers that result in excessive deviations from the original trajectory. Moreover, the nature of the resolution (change in route, altitude or speed) may not be user-preferred. Due to a lack of adequate traffic, weather, and airspace restriction information (and the means to present such information), and also a lack of conflict resolution tools on the flight deck, current procedures generally do not permit the user to effectively influence controller decisions on conflict resolution.

(b) ATSP often cannot accommodate the user's trajectory preferences for conformance with local TFM constraints.

The dynamic nature of both aircraft operations and NAS operational constraints often result in a need to change a 4-D trajectory plan while the aircraft is en route. Currently, the user (FD or AOC) is required to submit a request for a trajectory change to the ATSP for approval. During flow-rate constrained operations, the air traffic service provider (ATSP) is rarely able to consider user preferences for conformance. Additionally, a lack of accurate information on local traffic and/or active local TFM constraints (bad weather, special use airspace (SUA), airspace congestion, arrival metering/spacing) can result in the FD or AOC requesting an unacceptable trajectory. The ATSP is forced to plan and implement clearances that meet separation and local TFM constraints, but may not meet user preferences. Further negotiation between the ATSP and FD can adversely impact voice-communication channels and increase ATSP and FD workload.

4.2 SOLUTION (FLIGHT DECK FOCUS)

(a, b) Appropriately equipped aircraft accept the responsibility to maintain separation from other aircraft, while exercising the authority to freely maneuver in en route airspace in order to establish a new user-preferred trajectory that conforms to any active local TFM constraints.

While in the en route operational domain, appropriately equipped aircraft are given the authority, capability, and procedures needed to execute user-preferred trajectory changes without requesting ATSP clearance to do so. Along with this authority, the flight crew takes on the responsibility to ensure that the trajectory change does not generate near-term conflicts with other aircraft in the vicinity. The trajectory change should also conform to any active local TFM constraints (bad weather, SUA, airspace congestion, arrival metering/spacing). User-preferred trajectory modification may be generated by the FD with AOC input if appropriate, or generated entirely by the AOC and transmitted to the FD via datalink. The FD broadcasts its modified flight plan via datalink (includes notification of ATSP) immediately after initiation of trajectory modification; in most situations, this task is handled by on-board automation.

The ATSP monitors separation conformance for free maneuvering aircraft, and provides separation assurance for lesser-equipped aircraft using CD&R decision support tools (DSTs). The ATSP may act on behalf of lesser-equipped aircraft when they are in potential conflict with free maneuvering aircraft. For cases where the flight crew attempts, and fails, to resolve a conflict, automated systems or the ATSP will provide a required resolution. Procedures and flight rules are established that provide incentive for aircraft to equip for self-separation, such as, perhaps, priority status in conflicts with lesser-equipped aircraft.

4.3 POTENTIAL BENEFITS OF CE 5 OPERATIONS

The potential benefits of CE 5 operations are:

- Reduction in excessive and non-preferred deviations for separation assurance and local TFM conformance, due to the ability of the flight crew (for equipped aircraft) to self-separate and maintain local TFM conformance according to their preferences.
- Increased safety in separation assurance for all aircraft, due to communications, navigation, and surveillance (CNS) redundancy (FD as primary and ATC as backup) and increased situational awareness on the FD of appropriately equipped aircraft.
- Reduced ATSP workload for separation assurance and local TFM conformance plus reduced flight crew workload for communications, due to the distribution of responsibility for separation assurance and local TFM conformance between the ATSP and appropriately equipped FDs.

A detailed description of CE 5 can be found in Philips (2000).

5. DESCRIPTION OF CE 11: TERMINAL ARRIVAL: SELF-SPACING FOR MERGING AND IN-TRAIL SEPARATION

5.1 CURRENT PROBLEM

Excessive in trail spacing buffers in arrival streams reduce runway throughput and airport capacity, especially in conditions of poor visibility and /or low ceilings.

In terminal area environments for which arrival demand approaches or exceeds capacity, aircraft landing rates are significantly lower under instrument meteorological conditions (IMC) than under visual meteorological conditions (VMC). In order to compensate for uncertainties in aircraft performance and position, the ATSP applies in-trail spacing buffers to arrival streams under IMC in order to ensure that minimum separation requirements between successive aircraft are met. The resulting generous arrival spacing reduces runway throughput below its capacity to accept aircraft.

5.2 SOLUTION (FLIGHT DECK FOCUS)

Appropriately equipped aircraft are given clearance to merge with another arrival stream, and/or maintain in-trail separation relative to a leading aircraft.

In VMC, aircraft are often able to maintain closer spacing during the approach, thereby increasing the capacity of the terminal area and the runway acceptance rate. In the current system, the FD is often requested to accept responsibility for visual self-separation once they acknowledge they can see the leading aircraft. In this situation, the FD is responsible for determining and then maintaining a safe separation from other aircraft, and is therefore not subject to the ATSP minimum separation requirements.

Self-spacing operations will enable the FD to autonomously merge with another arrival stream and/or maintain in-trail separation with another aircraft under IMC as they would under VMC, thus significantly increasing arrival throughput. Self-spacing applies to aircraft that are subject to spacing requirements during arrival from the feeder fix up to the final approach fix.

Anticipated procedures for self-spacing involve the ATSP transferring responsibility for in-trail separation to properly equipped aircraft, while retaining responsibility for separating these aircraft from crossing traffic. Once the FD receives clearance to maintain spacing relative to a designated lead aircraft, the FD establishes and maintains a relative position with frequent monitoring and speed/course adjustments. Under some conditions, information such as required time of arrival (RTA) at the final approach fix may be provided by an appropriate ATSP-based DST, thereby enabling accurate inter-arrival spacing that accounts for differing final approach speeds or wake vortex avoidance. ATSP monitors all aircraft to ensure adequate separation. For cases where the flight crew fails to maintain adequate spacing, automated systems or the ATSP will provide a required correction.

The self-spacing concept is expected to make use of datalink capabilities to provide position information and a cockpit display of traffic information (CDTI) and/or advanced flight director/head-up guidance technology to provide spatial and temporal situation awareness to the flight crew. FD-based DSTs will provide information to enable station keeping and/or monitoring of automatic 4D trajectory management.

A detailed description of CE 11 can be found in Sorensen (2000).

5.3 POTENTIAL BENEFITS

The potential benefits of CE 11 operations are:

- Increased arrival capacity/throughput in IMC due to a reduction in excessive spacing buffers resulting from the ability of appropriately equipped aircraft to operate as if they were in VMC.
- Reduced ATSP workload, due to transfer of separation responsibility to the flight crew of appropriately equipped aircraft.

6. GUIDELINES

The literature review of NASA, FAA, and other capabilities made it clear that a number of existing capabilities can be used for investigating DAG-TM concepts. Yet it is noteworthy that the existing capabilities lack the following ability to:

- Model human performance characteristics; particularly taskload and workload, human error, and decision making,
- Simulate effects of weather,
- Simulate AOC operations,
- Simulate TFM operations, and
- Conduct gate-to-gate high-fidelity simulations.

It is also noteworthy that no fast-time simulation model completely incorporates human performance modules. However, the fast time simulations provide an early assessment of benefits. The fast-time results also indicate where the real-time simulation studies need to be focused (FAA, 1998).

6.1 GUIDELINES RELATED TO FAST-TIME MODELING AND SIMULATION

In the earlier TRL stages such as 1, 2, 3, and 4; fast-time simulations could serve as a quick and cost-effective way to examine preliminary benefits and compare alternate concepts, procedures, and functional allocation schemes.

6.1.1 Fast-time Models that Address Human Performance

Although there are a number of fast-time models that address human performance, based on the primary author’s prior experience, only a handful are being widely used. These include Reorganized ATC Mathematical System (RAMS), Performance and Usability Modeling in ATM (PUMA) and man-machine Integration, Design and Analysis System (MIDAS). These models are particularly chosen since they have been used in a number of FAA and Eurocontrol studies. These models are particularly useful in the early stages of concept exploration and hence the early TRLs. In particular, these models will examine the preliminary impact of different functional decomposition schemes that divide tasks and procedures. PUMA particularly addresses taskload and workload considerations. RAMS examines human workload as well as system benefits such as delay and throughput. MIDAS also examines the impact of task allocation schemes on the human operator.

6.1.2 Fast-time Models that Address System Performance

As indicated in the literature review, there are a number of fast-time models that examine system performance. However, the primary author's experience indicates that only handful models have been widely used and accepted. These models are also chosen because they can accommodate a wide range of requirements and are not limited to a specific airspace or airport.

A fast-time simulation model such as National Airspace System Performance Analysis Capability (NASPAC) should be used to examine NAS-wide system benefits such as capacity, delays, and fuel consumption. The FAA uses NASPAC.

Sector Design and Analysis Tool (SDAT) could also prove to be useful for examining modifications in airspace, routes, restrictions, procedures, and traffic mix on system capacity and delays. SDAT also offers a visualization tool.

Currently, the FAA is developing a fast-time infrastructure called Aviation Integrated Reasoning Modeling Matrix (AIRMM) to investigate gate-to-gate benefits of advanced concepts. Although AIRMM is not complete, NASA could consider collaboration with the FAA to complete the AIRMM. In addition, NASA is currently working on Virtual Airspace Model (VAM) (previously called Virtual Airspace Simulation Technology [VAST]) that will allow gate-to-gate simulations.

6.2 REAL-TIME HUMAN-IN-THE-LOOP SIMULATION CAPABILITIES

NASA Ames Research Center has one of the highest fidelity tower simulators (i.e., Future Flight Central). NASA Ames Research Center and NASA Langley Research Center have low and high fidelity cockpit simulators. However, both facilities have lower fidelity ATC simulators. These ATC simulators are adequate for conducting studies at early stages of TRLs (e.g., 1, 2, and 3). However, as the concepts mature and advance through the TRLs, higher fidelity simulations are necessary to demonstrate their feasibility and benefits. The higher fidelity ATC simulation capabilities such as Display System Replacement (DSR), Standard Terminal Automation Replacement System (STARS), Voice Switch Communication System (VSCS), and the Host processor would be beneficial for conducting higher fidelity simulation studies particularly at higher stages of TRLs (e.g., 5 and 6). A Research Task Order funded by NASA also identified a lack of higher fidelity ATC simulation capabilities (NASA Ames Simulator RTO58, 2001). The FAA William J. Hughes Technical Center (WJHTC) currently possesses all of these capabilities. Since these capabilities are very costly, it would be cost-effective to conduct higher fidelity simulation studies in collaboration with the FAA WJHTC.

Table 1 summarizes fast-time models and the real-time simulation capabilities that could be useful at different stages of TRLs.

Table 1. Summary of TRL Mapping Simulation Models and Capabilities

TRL	Name	Location	Category
1, 2, 3	Performance and Usability Modeling in ATM	NATS, U.K.	Fast-time simulation model for human performance
1, 2, 3	Reorganized ATC Mathematical System	FAA and Eurocontrol	Fast-time simulation model for human performance
1, 2, 3	Man-machine Integration, Design, and Analysis System	NASA Ames	Fast-time simulation model for human performance
1, 2, 3, 4	NAS Performance Assessment Capability	FAA	Fast-time simulation model for system performance
3,4,5,6	Future Flight Central	NASA Ames	Tower cab simulator
3,4,5	Air Traffic Operations Laboratory	NASA Ames	En route and terminal
3,4,5	Autonomous Operations Laboratory	NASA Langley	Flight deck
4,5,6	Flight Simulators (MD11, Advanced Cab, B747-400)	NASA Ames	Flight deck
3,4,5	Pseudo Aircraft Simulator	NASA Ames	Pseudo aircraft
3,4,5	Aviation System Analysis Capability	NASA Ames	Integrated suite of models and databases
1,2,3,4,5,6	Crew-Vehicle Systems Research Facility	NASA Ames	Flight deck simulator
3,4,5,6	CTAS Laboratory:	NASA Ames	En route and terminal domain with conflict probe
2,3	Stone Soup Simulator	NASA Ames	Flight deck
1,2,3,4,5,6	Virtual Airspace Simulation Technology/ Virtual Airspace Model	NASA Ames	Gate-to-gate capability
2,3,4	Virtual Laboratory	NASA Ames	Virtual Laboratory
2,3,4,5,6	Aviation Integrated Reasoning Modeling Matrix	FAA WJHTC	Modeling and simulation tool; Suite for gate-to-gate capability
2,3,4,5,6	Research Development Human Factors Laboratory	FAA WJHTC/RDHFL	Overall simulation environment
3,4,5,6	DSR En Route Host Laboratory	FAA WJHTC	Laboratory
3,4,5,6	STARS Laboratory	FAA WJHTC	Laboratory
3,4,5,6	ARTS Laboratory	FAA WJHTC	Laboratory
3,4,5,6	Target Generation Facility	FAA WJHTC	Modeling and Simulation support
2,3,4	AT Coach	FAA WJHTC/RDHFL	En route and terminal domain
2,3,4	Systematic Air Traffic Operations Research Initiative	FAA WJHTC	ATC replay
1,2,3,4,5,6	En Route Integration and Interoperability Facility	FAA WJHTC	En route domain
3,4,5,6	Dynamic Simulator	FAA ARTCC (all)	En route domain
3,4,5	ODS Tool Box	FAA WJHTC/RDHFL	Prototyping display
2,3,4,5, 6	Distributed Environment for Simulation Rapid Engineering and Experimentation	FAA WJHTC/RDHFL	En route and terminal domain

6.2.1 Additional Capability Requirements

The AOC and TFM elements need to be incorporated in the simulations in order to examine the benefits and feasibility of DAG-TM CEs. Therefore, it is recommended that NASA should acquire an AOC simulation capability. Additionally, the TFM component would be essential to examine the role of traffic management within the concept dynamic. One potential capability for the TFM application is NASA's Future Air Traffic Management Concept Exploration Tool (FACET). FACET can compute system characteristics such as capacity, delays, and dynamic density.

Current capabilities do not include an ability to simulate weather or the effects of weather on flight crew and ATSP performance. Such a capability is particularly important to ensure that we consider scenarios that require rerouting due to severe weather.

It would be also helpful to acquire a prototype capability such as ODS Tool Box to develop displays, conduct part-time simulation studies, and conduct requirements analysis and usability assessment studies.

FAA has developed the Distributed Environment for Simulation Rapid Engineering and Experimentation (DESREE) that simulates the ATC display. This capability offers considerable flexibility since changes in display parameters (such as font, color, datablock, etc.) can be altered from study to study. The DESREE also provides a very good capability for demonstrations that is useful in the introduction of a concept of operations to the user community.

The data collection capability of all simulators and their supporting software need to be examined to ensure that the metrics guidelines identified in Subtask 4 can be either collected or derived from the data collection. This effort will be undertaken in FY02. Preliminary examination has indicated the need to acquire, for example, the capability to record interval workload data using a workload assessment keypad.

Much like the Systematic Air Traffic Operations Research Initiative (SATORI) capability, we also need a time-synchronized joint air and groundside replay capability for the FD, particularly for the CDTI, and for the ATC operations that use Center TRACON Automation System (CTAS) elements. Such graphic replay along with any voice communications would be definitely useful for researchers.

6.3 GUIDELINES FOR FIDELITY ASSESSMENT

There are a number of simulation fidelity assessment methods (Kopardekar, 1999). Of particular interest, two fidelity methods developed by Kopardekar are very useful. The first method addresses the adequacy of a simulator for a particular simulation (Kopardekar, DiMeo & Stahl, 1997). The second method quantifies simulator fidelity and offers a method to conduct cost-benefit (Nouragas, Watts, Kopardekar, & Richards, 1998).

Often times, researchers are interested in determining if an available simulator offers adequate fidelity to meet the objectives of a simulation. The adequacy of a simulator can be determined as follows:

Step 1 - Identify all attributes that are important for the study objectives.

For example, if it is an air traffic control display simulator, it may be important to realistically represent the rate of aircraft turn, rate of climb and descent, aircraft data symbology, etc.

Step 2 – *Determine importance of these attributes in a simulation on a 1-7 rating scale.*

The importance rating can be obtained from users or subject matter experts. A rating of 1 on the scale means very low importance, 4 indicates moderate importance, and 7 indicates very high importance. The importance ratings of a simulation attribute may vary from one study to another depending on the study objectives.

Step 3 – *Determine performance of these simulator attributes in a test on 1-7 rating scale.*

In order to assess the performance, a representative test must be conducted. This test involves a study scenario. For example, an air traffic control display will involve the display of aircraft operating in certain airspace. The performance rating can be obtained from users or subject matter experts. A rating of 1 means very low performance, 4 on a rating-scale indicates moderate performance, and 7 indicates very high performance.

Step 4- Develop an importance-performance matrix, with importance in columns and performance in rows. Based on the ratings, the attributes are filled in the matrix. An example is shown Table 2 (Kopardekar et al., 1997).

Table 2 shows that the example simulator has high performance and high importance for the *aircraft data symbol* presentation attribute. It has low performance but very high importance for *climb rate* representation. This indicates that the simulator in question is not adequate for the study. Typically, a simulator will be adequate if all-important attributes (five bove rating on importance scale) have good performance (five bove on performance scale). If high importance is desired but low performance is experienced (three or below rating), the simulator is not adequate for the application. Low performance ratings are accepted if the attribute receives low importance ratings as well.

Table 2. Fidelity Assessment using Importance-Performance Relationship

Performance Rating	Importance Rating						
	1 Very Low Importance	2	3	4 Moderate Importance	5	6	7 Very High Importance
1 - Very Low Performance							*Climb rates*
2							
3							
4 - Moderate Performance				*Turn rates*			
5							
6							
7 - Very High Performance							*Aircraft data symbol*

This fidelity assessment method must be used prior to the selection of a simulator. If a simulator is found to be inadequate then either the simulator capability must be enhanced or another simulator that offers adequate fidelity must be chosen. The advantage of this method is that it is very easy to use, intuitive, and identifies clearly the attributes that need improvements.

The second method that quantifies simulation fidelity is useful when a researcher has a choice of simulators for a particular simulation. This method is described in detail in the Section A.6.3 of the appendix. This method should only be used when there is a need to accurately estimate fidelity and conduct fidelity-cost benefit trade-off. This method takes more time than the one presented above due to the necessary calculations. Also, the method requires a precise knowledge of all simulation attributes (e.g., lateral position accuracy).

7. RECOMMENDATIONS

The authors' review of NASA, FAA, and other capabilities made it clear that a number of existing capabilities can be used for investigating DAG-TM. Yet it is noteworthy that the existing capabilities lack the following capabilities to:

- Model human performance characteristics particularly task load,
- Generate effects of weather and incorporate in the simulation,
- Simulate AOC operations,
- Simulate TFM operations, and
- Conduct gate-to-gate high-fidelity simulations.

It is also noteworthy that no fast-time simulation model completely incorporates human performance modules, with the exceptions of RAMS, MIDAS, and PUMA. Thus the authors further recommend the following activities in the next year:

- Increased collaboration with WJHTC in order to benefit the conduct of high-fidelity simulations particularly at later TRL stages;
- Acquisition of DESREE simulator;
- Acquisition of RAMS, PUMA, and TOPAZ;
- Development of human performance models to complement MIDAS and PUMA;
- Acquisition of NASPAC to conduct NAS-wide fast time simulation to assess benefits;
- Further collaboration with FAA for the development of AIRMM and VAST to reduce duplication of effort and leverage available resources;
- Development of an AOC simulator;
- Acquisition of an ODS tool box to develop prototype displays and conduct part-task simulations;
- Development of a TFM simulator;
- Incorporating dynamic density metrics to model taskload during simulations, and
- Start adopting a methodology for assessing simulation fidelity.

8. CONCLUSION

The researchers have identified a number of guidelines related to simulation models, simulation capabilities, and simulator fidelity assessment. These guidelines would serve as a starting point for enhancing simulation capabilities.

This Page Intentionally Left Blank

APPENDIX A: SIMULATION RELATED LITERATURE REVIEW

A.1 FUNDAMENTALS OF SIMULATION

Simulation is widely recognized as one of the most important tools in the validation of concepts and in the acquisition of future systems (O'Briant, 2001). Simulation studies can be classified based on the fidelity requirements of simulators (e.g., low, medium, and high) and the scope of simulations (e.g., part-task or end-to-end). Another method of classification is based on the nature of models used for simulation (e.g., fast-time or real-time). *Fast-time simulation* mimics or emulates an operation using mathematical, statistical, and analytical methods. Generally, a fast-time simulation emulates an operation for a period of time using Monte-Carlo simulation or queuing methods. Fast-time simulation is useful in conducting analyses of capacity, delays, and efficiency. "Fast-time" refers to the shorter time needed to emulate the operation, since the simulation uses mathematical, statistical, analytical principles, and the power of computing. An *analytical model* of a system refers to an abstract representation. In most cases, analytical models represent the system behavior using mathematical expressions and formulas. *RT HITL* simulation mimics or emulates a system or operation using human participants. RT HITL normally uses operationally similar equipment for simulation. One purpose of RT HITL is to examine the impact of an operation on an operator. Since RT HITL emulates the reality of the operation as closely as possible, the time required for emulation is identical to actual system operation (FAA, 2000).

An important consideration in conducting simulations is the fidelity requirement. Fidelity indicates how well a simulator duplicates the system it is intended to represent. It is generally recognized that costlier higher fidelity simulators provide more precise information whereas the less expensive lower fidelity simulators provide less precise information (for the same objective). Therefore, tradeoffs between fidelity and cost of simulation must be carefully considered, particularly in the early TRLs. Fidelity assessment methods have been developed to quantify the fidelity of a simulator and simulation (Kopardekar, 1999; Nouragas, Watts, Kopardekar, & Richards, 1997; Kopardekar, DiMeo & Stahl, 1997). It is necessary to identify a simulation's fidelity needs. Procedural evaluations may require higher fidelity, whereas "what if" type analysis may test adequately using lower fidelity.

Another area of interest is fast-time modeling or simulation for human performance assessment. Although there is no substitute for RT HITL simulation for examining the impact of advanced concepts on human performance, it may be possible to consider fast-time simulations or models for early and preliminary assessments. Such early assessments then provide insight where further investigations are undertaken. MIT researchers (Odoni et al., 1997) have identified a range of techniques.

A.2 EXISTING AND PROPOSED SIMULATION FACILITIES AT NASA AND FAA

The researchers are aware of the NASA and FAA simulation facilities that currently exist and are undergoing development including NASA's Virtual Airspace Simulation Tool (VAST) and FAA's Aviation Integrated Reasoning Modeling Matrix (AIRMM). As appropriate, the researchers will identify their applications. The researchers will review the following existing and proposed facilities and models at NASA and FAA to identify their suitability for human factors evaluations across NASA's TRLs.

A.2.1 NASA FACILITIES

The researchers examined the strengths, fidelity, weaknesses, availability, cost and TRL applicability of the following NASA Ames and Langley facilities:

- Future Flight Central (FFC),
- Air Traffic Operations Laboratory (ATOL),
- Autonomous Operations Planner (AOP),
- Flight simulators (MD11, Advanced Cab, B747-400),
- Pseudo Aircraft Simulator (PAS),
- Aviation System Analysis Capability (a compilation of models and tools),
- Future Air Traffic Management Concept Exploration Tool (FACET),
- Crew-Vehicle Systems Research Facility (CVSRF),
- Center TRACON Automation System Laboratory (CTAS),
- Stone Soup Simulator, and
- Virtual Airspace Simulation Technology (VAST).

A.2.2 FAA FACILITIES

The researchers studied the strengths, fidelity, weaknesses, availability, cost, and TRL applicability of the following FAA WJHTC facilities:

- Aviation Integrated Reasoning Modeling Matrix (AIRMM),
- Research Development and Human Factors Laboratory (RDHFL),
- Display System Replacement (DSR) En Route Host Laboratory,
- Standard Terminal Automation Replacement System (STARS) Laboratory,
- Arrival Route Terminal System Laboratory (ARTS),
- Target Generation Facility (TGF),
- Reconfigurable Cockpit Simulator (RCS),
- AT Coach,
- Systematic Air Traffic Operations Research Initiative (SATORI),
- Distributed Environment for Simulation Rapid Engineering and Experimentation (DESREE), and
- En Route Integration and Interoperability Facility (EI^2F)

A.3 FAST-TIME AND ANALYTICAL MODELS

The researchers reviewed a battery of fast-time and analytical models for their strengths, weaknesses, fidelity and their suitability across TRLs. Models and fast-time simulation tools available to investigate concepts of ATM fall into several categories that include:

- Analytical capacity and delay models;
- Airport operations models;
- High and intermediate level fidelity airspace simulation models;
- Safety models;
- Conflict resolution models;
- Models for workload measurement;
- Airspace management, human factors;
- Cost-benefit models;
- Noise models;
- Investment models; and
- Tools to assist with the operation of models.

The preliminary literature review focuses on the following fast-time and analytical models:

- Airfield Capacity Model (ACM);
- The Airport Machine;
- Airspace Simulation (ACIM);
- Airspace Simulation (ASIM);
- Approximate Network Delays (AND);
- Automatic Radar Control for the years beyond 2000 (ARC2000);
- ASCENT
- AVENUE;
- Aviation System Analysis Capability (ASAC) Airport Capacity;
- Aviation System Analysis Capability (ASAC) Airport Delays;
- Banc De Test (BDT);
- DELAYS;
- DORATASK;
- FLOWSIM;
- Future Air Traffic Management Concept Exploration Tool (FACET);
- Heuristic Runway Movement Event Simulator (HERMES);
- Integrated Noise Model (INM);
- Man-Machine Integration, Design, and Analysis System (MIDAS);
- National Airspace Resource Investment Model (NARIM);
- National Airspace System Performance Capability (NASPAC);
- NLR ATC Research Simulator (NARSIM);

- NOISIM;
- Performance and Usability Modeling in ATM (PUMA)
- Reorganized ATM Mathematical System (RAMS);
- Robust Air Traffic Simulation Generator (RATSG);
- Sector Design Analysis Tool (SDAT);
- SIMMOD;
- TMAC;
- Total Airspace and Airport Modeler (TAAM); and
- Traffic Organization and Perturbation Analyzer (TOPAZ).

Hereafter, the simulation capabilities are described based on fast-time and RT HITL features. Each simulation capability is described in a standard tabular format with a brief explanation of its characteristics.

A.3.1 FAST TIME SIMULATION TOOLS, MODELS, AND ANALYTICAL MODELS

Name:(location)	**Category:**	**Status:**
Airfield Capacity Model (ACM): (CAASD, MITRE, FAA)	Airport Capacity	Mature
Inputs:	Runway, arrivals, departures, ATC separation, aircraft, weather (ceiling and visibility), standard deviations.	
Outputs:	Estimates capacity per hour using increments of 10%.	
Assumptions:	Configurations: single runway, closely spaced parallel, intermediate parallel, and intersecting runways. Taxiways have minimal impact on operations.	
Platform / Software:	Fortran.	
Strengths:	Quick estimates.	
Weaknesses:	Accuracy (assumes same number of departures as arrivals).	
TRL: 1, 2, 3.	**Supplemental Information: Analytical in nature.**	

Name: (location)		**Category:**	**Status:**
The Airport Machine: (Airport Simulation International)		Airport Capacity & Delays	Mature
Inputs:	Airport entered as node-link, schedule files, structure, up to 8 aircraft types, real time or automatic.		
Outputs:	Graphical interface, numbers for arrival, departures, gate occupancy times, towing statistics, numbers of aircraft at queues.		
Assumptions:	Assumes node-link structure for operations, take-off operations independent from routes past fix, can only perform single airport studies.		
Platform / Software:	PC+ Graphics card, TWO screens. MS-DOS.		
Strengths:	Fidelity, amount of details, GUI.		
Weaknesses:	Expense, (training time), Closed Architecture.		
TRL: 3, 4.	**Supplemental Information: None.**		

Name: (location)		**Category:**	**Status:**
Airspace Simulation (ACIM): (LMI, NASA) *see also ASAC Model(s)*		Cost benefit and investment	Developed
Inputs:	Demand variables, supply variables, network variables, capital attributes.		
Outputs:	Domestic and international travel demand, size of U.S. passenger fleet, operating margin for U.S. fleet.		
Assumptions:	Past trends can be applied to future.		
Platform / Software:	PC. MS Excel, Lotus.		
Strengths:	Ease of use, tested extensively, GUI.		
Weaknesses:	Assumes past results will predict future.		
TRL: 2.	**Supplemental Information: Analytical in nature.**		

Name: (location)		**Category:**	**Status:**
Airspace Simulation (ASIM): (DRA, CAA/ NATS)		Airspace Complexity, en route simulation	Developing, basic engine functional
Inputs:	Node-link routing structure, sector definitions, aircraft performance characteristics and altitude boundaries, flight plans, statistical information about the number and frequency of flights between city pairs.		
Outputs:	Detailed report about close encounters of aircraft.		
Assumptions:	Assumes a fixed route structure, no weather model, random variables introduced will generate a representative sample of AT.		
Platform / Software:	DEC Alpha. Modsim, C & C++.		
Strengths:	Unknown.		
Weaknesses:	Limited documentation, under development.		
TRL: 3, 4.	**Supplemental Information: None.**		

Name: (location)		Category:	Status:
Approximate Network Delays (AND): (MIT, MITRE)		Airport Delays	Complete
Inputs:	Capacity profile, demand profile for arrivals and departures, schedule of flights.		
Outputs:	Probability vectors, queue length, waiting time, total delay suffered, fraction of aircraft delayed at each airport by time, local delay and “upstream delay”.		
Assumptions:	Does not model en route congestion, assumes that airports are weakly connected, (no airport receives more than 25% of its flights from any other single airport).		
Platform / Software:	SunSparc10. (Serial and parallel).		
Strengths:	Modular, good for policy level studies, GUI.		
Weaknesses:	Unknown.		
TRL: 1, 2, 3.	**Supplemental Information: Analytical in nature.**		

Name: (location)		Category:	Status:
Automatic Radar Control for the years beyond 2000 (ARC2000): (Eurocontrol, FAA)		Airspace Traffic Management and control	Developed (Frozen)
Inputs:	Simulated airspace, (description, traffic samples), maneuver priorities/ parameters, sequencing points, deviation thresholds, lateral & vertical separations between aircraft, time horizon for conflict resolution.		
Outputs:	Aircraft density, conflict density, trajectory deviations, unresolved conflicts, extra route distances, etc.		
Assumptions:	Each aircraft is equipped with 4D FMS, datalinks have infinite bandwidth, computational power is infinite, conflict resolution is automatic.		
Platform / Software:	HP9000/ 755. ADA and ANSI-C.		
Strengths:	Highly interactive problem solver (HIPS), system well documented, modular, fast learn time, no human machine interface (HMI) for controllers.		
Weaknesses:	Capacity, resolution.		
TRL: 4.	**Supplemental Information: None.**		

Name: (location)	**Category:**	**Status:**
ASCENT: (NASA)	Air Traffic Flow Management (ATFM)	Developed / evolving
Inputs:	Flight schedules, airport capacity.	
Outputs:	Scheduled, planned, and realized itinerary for each aircraft, statistical measures.	
Assumptions:	Assumes terminal areas are congestion points.	
Platform / Software:	MAC C	
Strengths:	Easy to use, GUI.	
Weaknesses:	New, lack of adequate documentation.	
TRL: 1, 2, 3.	**Supplemental Information: None.**	

Name: (location)	**Category:**	**Status:**
AVENUE: (Eurocontrol) /Assembly of a Generic Airborne ATM Platform (AGAAP): (DERA)	Future ATM Concept simulation system	Under Development
Inputs:	Unknown.	
Outputs:	Unknown.	
Assumptions:	Unknown.	
Platform / Software:	PC.	
Strengths:	Modular, GUI, Designed for use with future systems, 4-D, high fidelity.	
Weaknesses:	Unknown.	
TRL: 1, 2, 3, 4.	**Supplemental Information: None.**	

Name: (location)	**Category:**	**Status:**
Aviation System Analysis Capability (ASAC) Capacity: (LMI, NASA)	Airport Capacity (and runway capacity)	Developed / evolving
Inputs:	Inputs depend on desired outputs and can be modified to reflect different parameters. Separation standards, weather information, operational rules, airport specific data.	
Outputs:	Arrival runway occupancy time, arrivals versus departures, capacity curves.	
Assumptions:	Assumes past history reflects future history, assumes traffic appear at random, does not include surface movement component.	
Platform / Software:	PC. Pascal / C.	
Strengths:	Easy to use, modular, can be applied to multiple airports with multiple runways, networked, (Terminal, ARTCC sectors, TRACONS), modular, weather, GUI.	
Weaknesses:	Reliance on past history, fidelity.	
TRL: 3, 4.	**Supplemental Information: Analytical in nature.**	

Name: (location)	Category:	Status:
Aviation System Analysis Capability (ASAC) Delays: (LMI, NASA)	Airport Delays	Developed / evolving
Inputs:	Results of ASAC Airport Capacity Model (may be substituted with airport specific data in proper format), capacity curves, selected configuration capacity, weather data.	
Outputs:	Expected arrival delays, demand and capacity for one hour increments.	
Assumptions:	Same ratio of arrivals as departures, does not account for airline scheduling practices, does not account for cancellations due to severe weather, does not reflect earlier than expected arrivals.	
Platform / Software:	PC. Pascal / C.	
Strengths:	Speed, non-biased for existing congestion, GUI.	
Weaknesses:	Validation, fidelity.	
TRL: 3, 4.	**Supplemental Information: Analytical in nature.**	

Name: (location)	Category:	Status:
Banc De Test (BDT): (CENA)	Simulation tool, test auto conflict resolution	Evolving
Inputs:	Location of navigation beacons, basic aircraft performance data, flight plans.	
Outputs:	Departure time, arrival time, delay time, number of aircraft and altitudes at five-minute intervals, conflict details.	
Assumptions:	Aircraft trajectories are simplified, aircraft climb to cruise flight level at a constant speed and rate of climb, airspeed and altitude are constant during cruise, descent parameters same as ascent, etc.	
Platform / Software:	Unix, SunSparc5. GNU C compiler, C.	
Strengths:	Modular, well-organized, tactical level, GUI.	
Weaknesses:	Limited capabilities, no formal user's guide.	
TRL: 1.	**Supplemental Information: None.**	

Name: (location)	Category:	Status:
DELAYS:(MIT)	Airport Delays	Complete
Inputs:	Capacity profile and demand profile, order of the probability distribution.	
Outputs:	Probability vector, expected queue length of time, expected waiting time, total delay, fraction of aircraft delayed.	
Assumptions:	Airport represented as a queuing system, demand rate and capacity can be dynamic.	
Platform / Software:	PC / MAC. Pascal, C.	
Strengths:	Parametric studies.	
Weaknesses:	Fidelity.	
TRL: 1, 2.	**Supplemental Information: Analytical in nature.**	

Name: (location)		Category:	Status:
DORATASK: (CAA, UK)		Workload modeling	Developed
Inputs:	Sector geometry, routes, task timings.		
Outputs:	Workload limited sector limits.		
Assumptions:	Availability of activity times, designed for UK.		
Platform / Software:	Unknown.		
Strengths:	Works well for UK.		
Weaknesses:	Calibration, no available documentation, high level of learning effort.		
TRL: 1, 2, 3.	**Supplemental Information: Human performance.**		

Name: (location)		Category:	Status:
FLOWSIM: (Metron Inc., ATAC, FAA)		Traffic flow	Prototype
Inputs:	ETMS data.		
Outputs:	Delay metrics.		
Assumptions:	Aircraft assumed to fly predefined flight plans, delays are a function of miles-in-trail restrictions and airport capacity constraints.		
Platform / Software:	(platform not defined). C++.		
Strengths:	Fast run time.		
Weaknesses:	Experimental, not mature.		
TRL: 1.	**Supplemental Information: None.**		

Name: (location)		Category:	Status:
Future ATM Concepts Evaluation Tool (FACET): NASA		System wide concept exploration, Air Traffic Flow Management	Developed / evolving
Inputs:	Flight plans, schedules, tracks, weather data, airspace boundaries, airways, NAVAIDS, airports, aircraft models.		
Outputs:	System performance, system stability, conflict detection and resolution, dynamic density.		
Assumptions:	Unknown		
Platform / Software:	Sun, SGI, PC, and MAC. C and Java.		
Strengths:	GUI, 4-D capabilities, includes weather, modular, able to add new aircraft and spacecraft, can be used for interactive and off-line evaluations.		
Weaknesses:	Models ARTCCs only (not TRACON).		
TRL: 3, 4.	**Supplemental Information: None.**		

Name: (location)	Category:	Status:
Heuristic Runway Movement Event Simulator (HERMES): (CAA / NATS)	Parallel Runway Capacity (and Tower controller workload)	Evolving (used only in England)
Inputs:	Traffic recordings (4-D) (mainly Heathrow and Gatwick data).	
Outputs:	File containing average delays. C and Excel Macros, delay statistics and graphs.	
Assumptions:	Custom designed for Heathrow and Gatwick airports, uses experimental trajectories instead of link-node structure.	
Platform / Software:	PC. C.	
Strengths:	Accuracy for Heathrow and Gatwick.	
Weaknesses:	Cannot model situations involving runway crossings, uncertainty of accuracy for use outside of England.	
TRL: 4.	**Supplemental Information: None.**	

Name: (location)	Category:	Status:
Integrated Noise Model (INM): (FAA)	Community noise impact	Developed
Inputs:	Aircraft flight profile, ARTS data, OAG data.	
Outputs:	Noise contour levels (NEF), Equivalent Sound Level (Leq), Day-Night Average Sound Level (Ldn) Time Above threshold of Weighted Sound (TA).	
Assumptions:	Aircraft trajectories are straight or curved, based on ARTS data, or through OAG schedules.	
Platform / Software:	PC. Windows NT.	
Strengths:	Well documented, GUI.	
Weaknesses:	Limitations due to wind modeling.	
TRL: 2.	**Supplemental Information: Analytical in nature.**	

Name: (location)	Category:	Status:
Man-Machine Integration, Design, and Analysis System (MIDAS): (NASA)	Human Factors and performance analysis	Evolving (29 modules)
Inputs:	(For Air-MIDAS): Mission and objectives to be performed, operator characteristics, additional modules.	
Outputs:	Human Factors analysis, visualization of simulated mission scenario, measurements of mission and operator performance, information requirements analysis	
Assumptions:	Human operates according to a set of definable decision rules	
Platform / Software:	Silicon Graphics Onyx, IRIX 5.2. C, C++, Allegro, Common LISP 4.2, CLIM 2.0.	
Strengths:	Modular, multi-dimensional, GUI.	
Weaknesses:	Very complex, slow simulation speeds, verification.	
TRL: 1, 2, 3, 4.	**Supplemental Information: Human Performance.**	

Name: (location)		Category:	Status:
National Airspace Resource Investment Model (NARIM): (FAA, NASA)		Modeling and analysis of future aviation system concepts	Under development
Inputs:	Inputs vary according to analysis performed, aircraft performance, weather, spatial/ temporal mapping, etc.		
Outputs:	Outputs vary, sector loading, travel times, assigned delays, en route/ arrival/ departure delays, workload, conflict potential and analysis, etc.		
Assumptions:	Assumptions of various models used within NARIM.		
Platform / Software:	PC, (MAC). UNIX OS, C, C++.		
Strengths:	GUI.		
Weaknesses:	Unknown.		
TRL: 1, 2, 3, 4.	**Supplemental Information: None.**		

Name: (location)		Category:	Status:
National Airspace System Performance Capability (NASPAC): (MITRE, CSSI, CENA)		System-wide, AT flows and delays	Developed
Inputs:	Demand, complete aircraft itinerary schedule, capacities, modeled fixes, en route sectors, aircraft performance data.		
Outputs:	Estimates of delay, flows of past given points, “technical delays”, “effective delays”.		
Assumptions:	Modeling of resources is at low level of detail.		
Platform / Software:	SUN. Simscript II.5, Fortran, C, and Pascal.		
Strengths:	Good for tactical Studies, GUI.		
Weaknesses:	Training, limited availability of labs.		
TRL: 4.	**Supplemental Information: None.**		

Name: (location)		Category:	Status:
NLR ATC Research Simulator (NARSIM): (NLR)		ATC Simulation	Mature
Inputs:	Comprehensive data on environment and agents, computer generated traffic		
Outputs:	Recordings of simulation can be made for post analysis of events and agent or system performance.		
Assumptions:	System utilizes airspace simulation of Netherlands and neighboring European countries.		
Platform / Software:	HP 9000.		
Strengths:	Modular, multi-dimensional, use of real data, GUI.		
Weaknesses:	Lab availability.		
TRL: 1, 2, 3.	**Supplemental Information: None.**		

Name: (location)	**Category:**	**Status:**
NOISIM: (MIT)	Community noise impact	Prototype
Inputs:	Programmed flight plans, an input device, wind conditions.	
Outputs:	Noise contours, sound metrics.	
Assumptions:	Calculations based on steady state of engines.	
Platform / Software:	Silicon Graphics. C.	
Strengths:	Accuracy, GUI.	
Weaknesses:	Limited stage of development.	
TRL: 4.	**Supplemental Information: Analytical and fast-time simulation.**	

Name: (location)	**Category:**	**Status:**
Performance and Usability Modeling in ATM (PUMA): (DRA)	Human Factors workload	Developed
Inputs:	Required tasks, AT scenarios, other data files, video recordings, etc.	
Outputs:	Graphs of workload against time, and activities with timelines.	
Assumptions:	Unknown.	
Platform / Software:	UNIX, MAC. Lisp based.	
Strengths:	Integrated tools, has fully integrated video analysis system.	
Weaknesses:	Verification unknown.	
TRL: 4.	**Supplemental Information: Human Performance, analytical in nature.**	

Name: (location)	**Category:**	**Status:**
Reorganized ATC Mathematical Simulator (RAMS): (Eurocontrol, FAA)	ATC Modeling, En route/ terminal and controller workloads, free flight study	Developed / evolving
Inputs:	Airspace description, rule-based resolutions, conflict probes, separation values, flight plan description, workload analysis, weather patterns.	
Outputs:	Distribution of workload, traffic loads, traffic penalties, frequency distributions.	
Assumptions:	Unknown.	
Platform / Software:	HP9000. Modsim II, Unix X-Windows, HP-Vue.	
Strengths:	Multipurpose, fast-time, can be used with or without conflict resolution.	
Weaknesses:	Poor post processing capabilities, closed architecture.	
TRL: 1, 2, 3.	**Supplemental Information: Human Performance.**	

Name: (location)	Category:	Status:
Robust Air Traffic Simulation Generator (RATSG): (MIT, NASA)	4 D flight paths of pseudo aircraft	Operational
Inputs:	Type of aircraft, call sign, transponder status, TCAS, aircraft initial states, 4D waypoints, scripted voice messages.	
Outputs:	Aircraft state data in real time or fast time	
Assumptions:	Aircraft use simple point-mass dynamics.	
Platform / Software:	Silicon Graphics Indigo workstations. C, GL.	
Strengths:	Modular, GUI.	
Weaknesses:	Validation.	
TRL: 2.	**Supplemental Information: None.**	

Name: (location)	Category:	Status:
Sector Design Analysis Tool (SDAT): (FAA)	Workload analysis tool	Under development
Inputs:	Airspace data (sector boundaries, NAVAIDSs, fixes, routes, from ACES and adaptation data, AT data (ARTS, SAR, CDR, ETMS), and supplemental data (SUA).	
Outputs:	3D conflict analysis, areas needing more separation, expected sectors of conflicts, expected frequency congestion, traffic volumes, impacts on users from changes, flight times, flight distance, sectors traversed, financial costs, sector controller task loads.	
Assumptions:	Dependence on recorded traffic.	
Platform / Software:	HP-UX, Sun systems. C, UNIX X-Windows.	
Strengths:	User friendly, On-line help, GUI.	
Weaknesses:	Dependence on recorded traffic.	
TRL: 4.	**Supplemental Information: Analytical in nature.**	

Name: (location)	Category:	Status:
SIMMOD: (FAA)	Airfield, Terminal, En Route, Regional.	Mature
Inputs:	Specification of network structure for airfield/ airspace, (flight plans).	
Outputs:	Detailed statistics: aircraft travel times, traffic flows, throughput capacity, delays, reasons for delays, fuel consumption.	
Assumptions:	Traffic moves on preset network of nodes and links, (1) dimensional model, does not check for lateral or vertical separation violations.	
Platform / Software:	Sun or HP, UNIX or DOS. SIMSCRIPT II.5, C.	
Strengths:	High fidelity, low acquisition cost, GUI.	
Weaknesses:	High labor costs, not good for free flight studies, and modeling local congestion.	
TRL: 3.	**Supplemental Information: None.**	

Name: (location)	Category:	Status:
TMAC: (MITRE)	Simulation tool, traffic studies	Evolving (MITRE internal use only)

Inputs:	Aircraft routes, flight plans, aircraft dynamics, ground delays, traffic management logic, airport capacity.
Outputs:	Travel times, delays, conflicts.
Assumptions:	Assumes given airport capacities, but no en route sector capacities, no conflict resolution algorithms are included.
Platform / Software:	HP-UX 755. HP-UX 9.0.3, Sybase 4.9.2, Vads 6.2, Perl, C, ADA.
Strengths:	High level of detail.
Weaknesses:	Availability, no conflict resolution.
TRL: 1, 2, 3.	**Supplemental Information: None.**

Name: (location)	Category:	Status:
Total Airspace & Airport Modeler (TAAM): (Preston Group, DFS, NATS/ *British* CAA, STCA, Swiss Control, NLR, CSF, FAA Southern region & Potomac, NASA, NY Port Authority, and others)	Air Traffic Simulation	Developed, fully functional

Inputs:	Airport descriptions, airspace route/sector layouts, geographical features, ATC rules, airport usage rules, traffic time tables, aircraft trajectories/ routes, aircraft performance characteristics, conflict detection/ resolution strategies.
Outputs:	System delays/ conflicts, airport movements/ delays/ operations, airspace operation metrics, noise contours, fuel consumption, controller workload, individual aircraft profiles, scenario generation, “showlogic”, text messages, errors, 2D, 3D, visualization.
Assumptions:	Hazardous weather, and special use airspace have limited dynamic viewing.
Platform / Software:	SunSparc20 or higher.
Strengths:	4D model, 2D, 3D visualization, realism, flexibility, ease of use, GUI.
Weaknesses:	Expensive acquisition and technical support costs, limitations in conflict avoidance.
TRL: 3.	**Supplemental Information: Human Performance.**

Name: (location)		Category:	Status:
Traffic Organization and Perturbation Analyzer (TOPAZ): (NLR)		Collision risk, analysis of Free Flight ATM	Operational, evolving
Inputs:	Description of the operational ATM concept to be evaluated, Statistical characteristics of AT scenarios to be evaluated, identification of hazards, high level Petri net model, parameter ranges.		
Outputs:	Evaluation of safety characteristics of new operational ATM concept.		
Assumptions:	Level of detail is limited.		
Platform / Software:	PC.		
Strengths:	Highly modular, GUI.		
Weaknesses:	Less detailed than fast-time simulations.		
TRL: 1, 2, 3.	**Supplemental Information: Analytical and fast-time simulation.**		

Most of these models, which are analytical in nature, seem more suited to lower order TRL requirements. Conversely, models with higher level fidelity, fit better with higher level TRL requirements. It may be advantageous to pair analytical models with compatible fast time models and tools to effectively investigate a concept from lower order TRL levels through the higher level TRLs.

A model's modularity and compatibility with other models is a key factor to consider. Many new aerospace concepts require a model to be flexible. Proprietary models may not be able to work in tandem with other models. Several older, highly validated models, such as SIMMOD, lack the ability to evolve and explore new concepts. Some models such as TAAM and RAMS appear to have the ability to evolve and handle issues involved in the study of free flight. Models that run on various platforms may be more advantageous than models that can only run on a single platform. Models which are airspace or environment specific, such as HERMES, may not accurately model other airspace. There is a lack of available models that measure human factors and man-machine integration.

A.3.2 HUMAN PERFORMANCE MODELS

Preliminary assessment of Eurocontrol's Reorganized ATC Mathematical System (RAMS) has shown that it needs improvements in the tasks (Schwartz & Kopardekar, 2000). Another possible fast-time modeling tool for early examination of ATC concepts is Man-machine Integration Design and Analysis System (MIDAS). MIDAS provides designers with a platform for analyzing human-system integration in an environment in which both cognitive human function and intelligent machine function are described in similar terms (Corker & Smith, 1993). Both MIDAS and PUMA are relatively new with respect to validating human response and measurement.

A.4 RT HITL CAPABILITIES

A.4.1 NASA CAPABILITIES

Name: (Location)	**Category:**	**Status:**
Future Flight Central: (NASA Ames)	Tower Cab Simulator (360-degree high fidelity visual simulator)	Developed
Inputs:	SIMMOD, TAAM, and other airport planning tools.	
Outputs:	Plan runways, test ground traffic / tower communications, and validate AT planning simulations.	
Strengths:	High fidelity, modular compatibility.	
Weaknesses:	Unknown.	
TRL: 3, 4, 5, 6.		

Name: (Location)	**Category:**	**Status:**
Air Traffic Operations Laboratory: (NASA Ames)	En Route and Terminal Operations	Developed
Inputs:	Flight plans.	
Outputs:	Capacity, delays, conflicts, and time in sectors.	
Strengths:	Flexible.	
Weaknesses:	Lower fidelity than operational system.	
TRL: 3, 4, 5.		

Name: (Location)	**Category:**	**Status:**
Autonomous Operations Planner: (NASA Langley)	En Route and Terminal Operations	Developed
Inputs:	Flight plans.	
Outputs:	Capacity, delays, conflicts, and time in sectors.	
Strengths:	Flexible.	
Weaknesses:	Lower fidelity than operational system.	
TRL: 3, 4, 5.		

Name: (Location)	**Category:**	**Status:**
Flight simulators (MD11 [NASA Langley], Advanced Cab, B747-400 [NASA Ames])	Simulator	Developed
Inputs:	Aircraft performance characteristics, scenario specifications.	
Outputs:	Fuel burn, duration, and other system performance.	
Strengths:	High fidelity, modularity, well documented.	
Weaknesses:	Limited number of high level simulators to participate in simulation(s).	
TRL: 4, 5, 6.		

Name: (Location)		**Category:**	**Status:**
Pseudo Aircraft Simulator (PAS): (NASA Ames)		Simulator	Developed
Inputs:	Simulation requirements.		
Outputs:	Simulated aircraft, piloted by pseudo-pilots.		
Strengths:	Flexibility, increases realism of simulation, adds flexibility.		
Weaknesses:	Flight dynamics is not perfect.		
TRL: 3, 4, 5.			

Name: (Location)		**Category:**	**Status:**
Aviation System Analysis Capability: (NASA Ames)		Integrated suite of models and databases.	Developed / evolving.
Inputs:	Analytical tools and studies.		
Outputs:	Evaluates technology impacts, policies, and procedures.		
Strengths:	Well documented, range of models to choose from.		
Weaknesses:	Unknown.		
TRL: 3, 4, 5.			

Name: (Location)		**Category:**	**Status:**
Crew-Vehicle Systems Research Facility (CVSRF): (NASA Ames)- It houses NASA Ames 757 and 747-400		Studies human factors in aviation safety.	Developed / evolving.
Inputs:	Various human factors studies.		
Outputs:	Performance characteristics in flight crews, formulate design criteria and principles for future aviation environments, evaluate ATC procedures, and develop new training and simulation techniques.		
Strengths:	Unknown.		
Weaknesses:	Unknown.		
TRL: 1, 2, 3, 4, 5, 6.			

Name: (Location)		**Category:**	**Status:**
Center TRACON Automation System (CTAS): Laboratory (NASA Ames)		Laboratory, Conflict probe	Developed
Inputs:	Relative performance data.		
Outputs:	Generates AT advisories to increase fuel efficiency, provides automation to assist with aircraft sequencing, and separation, provides automation tools for planning and controlling arriving AT.		
Strengths:	High Fidelity.		
Weaknesses:	Unknown.		
TRL: 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Stone Soup Simulator: (NASA Ames)		Simulator Software for FD	Developed
Inputs:	Flight plan data.		
Outputs:	Fuel efficiency, distance traveled.		
Strengths:	Flexible, can be used on a desktop Unix station.		
Weaknesses:	Low fidelity, not well documented.		
TRL: 2, 3.			

Name: (Location)		Category:	Status:
Virtual Airspace Simulation Technology: (NASA)		Simulation of NAS	Being developed
Inputs:	Connects simulators using High-level architecture (HLA).		
Outputs:	NAS wide system performance data (gate to gate).		
Strengths:	One of the few gate-to-gate simulation capabilities, suitable for fast-time as well as RT HITL.		
Weaknesses:	It would take time to develop and validate such capability.		
TRL: 1,2,3,4,5,6.			

Name: (Location)		Category:	Status:
Virtual Laboratory (VLAB): (NASA Ames)		Virtual Laboratory	Evolving
Inputs:	Variable, depending on requirements of study.		
Outputs:	Variable, depending on requirements of study.		
Strengths:	Modularity, rapid prototyping.		
Weaknesses:	Unknown.		
TRL: .2, 3, 4.			

A.4.2 FAA CAPABILITIES

Name: (Location)		Category:	Status:
Aviation Integrated Reasoning Modeling Matrix (AIRMM): (WJHTC)		Modeling and simulation tool / suite	Evolving
Inputs:	Variable depending on required outputs.		
Outputs:	Integrated models and modular components to be used for simulations.		
Strengths:	High fidelity, modularity, comprehensive knowledge base.		
Weaknesses:	Unknown.		
TRL: 2, 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Research Development and Human Factors Laboratory (RDHFL): (WJHTC)		Human Factory Laboratory	Developed / evolving
Inputs:	Subject matter experts, NAS specifications, variable depending upon requirements.		
Outputs:	Simulations, HITL studies, variable depending upon requirements.		
Strengths:	High level of fidelity, modularity.		
Weaknesses:	Voice-communications system, lab availability.		
TRL: 2, 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Display System Replacement En Route Host Laboratory: (WJHTC)		Laboratory	Developed / evolving
Inputs:	NAS system specifications.		
Outputs:	Simulations, system performance metrics, high fidelity.		
Strengths:	High fidelity and high flexibility.		
Weaknesses:	Lab availability.		
TRL: 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Standard Terminal Automation Replacement System Laboratory: (WJHTC)		Laboratory	Developed / evolving
Inputs:	Flight plans, sector information.		
Outputs:	NAS system performance.		
Strengths:	High fidelity.		
Weaknesses:	Low flexibility to explore new concepts.		
TRL: 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Arrival Route Terminal System Laboratory: (WJHTC)		Laboratory	Developed / evolving
Inputs:	Flight plans, sector information.		
Outputs:	Terminal system performance data.		
Strengths:	High fidelity.		
Weaknesses:	Low flexibility to explore new concepts.		
TRL: 3,4,5,6.			

Name: (Location)		Category:	Status:
Target Generation Facility (TGF): (WJHTC)		Modeling and Simulation support.	Fully developed
Inputs:	Aircraft performance characteristics, Sim Pilot commands.		
Outputs:	Simulated aircraft for both NAS and ARTS laboratories.		
Strengths:	High fidelity, capabilities to simulate one or more facilities, high flexibility		
Weaknesses:	Lab availability.		
TRL: 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
AT Coach: (WJHTC)		En route and terminal airspace simulation	Developed
Inputs:	Flight plans and sector information.		
Outputs:	NAS system performance data.		
Strengths:	Medium fidelity.		
Weaknesses:	Low flexibility.		
TRL: 2, 3, 4.			

Name: (Location)		Category:	Status:
Systematic Air Traffic Operations Research Initiative (SATORI): (WJHTC and ARTCC's).		Simulation / Replay	Mature
Inputs:	SAR data, ACES data, DART (conflict alert, track, and log) files, NTAP (weather and beacon) data files.		
Outputs:	Recreation of recorded files, and review of operational incidents.		
Strengths:	Provides assistance to accident investigations, acts as a tool to assist with management issues and airspace planning.		
Weaknesses:	Limited capabilities, documentation, closed architecture.		
TRL: 2, 3, 4.			

Name: (Location)		Category:	Status:
En Route Integration and Interoperability Facility (EI^2F): (WJHTC)		ARTCC Simulator	Developed / evolving
Inputs:	NAS Data, simulation requirements.		
Outputs:	Simulation.		
Strengths:	High fidelity, reconfigurable.		
Weaknesses:	Lab availability, communications system.		
TRL: 1, 2, 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
Dynamic Simulation Facility (DYSIM): (FAA ARTCCs)		En route airspace simulator	Developed
Inputs:	Scenarios with NAS specifications.		
Outputs:	Simulation, ability to test procedures and management objectives.		
Strengths:	Mid to high level fidelity, well documented, familiarity of system.		
Weaknesses:	Low flexibility for display and airspace modifications.		
TRL: 3, 4, 5, 6.			

Name: (Location)		Category:	Status:
ODS Tool Box: (WJHTC)		General Purpose design tool with interactive GUI	Developed
Inputs:	Variable, depending on required outputs.		
Outputs:	Visual display on workstation monitors.		
Strengths:	High fidelity, modular, reconfigurable, well documented, high flexibility.		
Weaknesses:	Time consuming development		
TRL: 3, 4, 5.			

Name: (Location)		Category:	Status:
Distributed Environment for Simulation Rapid Engineering and Experimentation: (FAA)		En route and terminal airspace simulations	Developed / evolving
Inputs:	Flight plans, sector information, new concepts.		
Outputs:	NAS system performance.		
Strengths:	High flexibility to change display characteristics, high fidelity, good data collection modules for human and NAS performance.		
Weaknesses:	Limited availability.		
TRL: 2, 3, 4, 5.			

A.4.3 TRL MAPPING OF CAPABILITIES

Tables A-1 and A-2 summarize the above capabilities using TRL mapping.

Table A-1. Summary of TRL Levels with Fast-Time and Analytical Models

TRL Level	Analytical Models	Simulation Models	Human Performance Measurements
TRL 1 • Develop operational concept • Perform trade and feasibility studies • High-level risk analysis • Identify benefit mechanisms • Identify research issues	ACM AND DELAYS NARIM TOPAZ	ASCENT AVENUE BDT DORATASK FLOWSIM MIDAS NARIM NARSIM RAMS TMAC TOPAZ NASPAC	DORATASK MIDAS RAMS
TRL 2 • Develop research plan • Identify critical feasibility issues • Research activities (performance improvements, human effectiveness and acceptance, preliminary specifications, algorithm development) • Software/hardware development plan • Benefit and safety assessment plan • Operational concept refinement • Initial single year benefit assessment	ACIM ACM AND DELAYS INM NARIM TOPAZ	ASCENT AVENUE DORATASK MIDAS NARIM NARSIM RAMS RATSG TMAC TOPAZ NASPAC	DORATASK MIDAS RAMS
TRL 3 • Develop initial requirements • Conceptual design/ architecture • Develop conceptual prototype • Workstation laboratory testing • Human interface design • Initial procedures, roles, and responsibilities	ACM AND ASAC (Capacity) ASAC (Delays) NARIM TOPAZ	ASCENT ASIM AVENUE DORATASK FACET MIDAS NARIM NARSIM RAMS SIMMOD TAAM The Airport Machine TMAC TOPAZ NASPAC	DORATASK MIDAS RAMS TAAM

Table A-1. Summary of TRL Levels with Fast-Time and Analytical Models (Cont.)

TRL Level	Analytical Models	Simulation Models	Human Performance Measurements
TRL 4 • Requirements update • Design/ architecture update • Develop research prototype • Integrated simulation testing of linked components (as appropriate for concept) • Possible shadow testing at field site • Updated procedures, roles, and responsibilities • Feasibility evaluations • Life-cycle benefits	ASAC (Capacity) ASAC (Delays) PUMA SDAT	ARC2000 ASIM AVENUE FACET HERMES MIDAS NARIM NASPAC NOISIM The Airport Machine	MIDAS PUMA
TRL 5 • Pre-development prototype evaluation with system development team involvement • Off-nominal conditions evaluations • Field testing (shadow tests/ possibly limited control of live traffic)	None	None	None
TRL 6 • Final high fidelity, integrated system demonstration of transfer prototype • Large variety of scenarios • Off-nominal scenarios • Finalize documentation for tech transfer	None	None	None

Table A-2. Summary of TRL Mapping and RT HITL Simulation Capabilities

TRL	Name	Location	Category
3,4,5,6	Future Flight Central	NASA Ames	Tower cab simulator
3,4,5	ATOL	NASA Ames	En route and terminal
3,4,5	AOP	NASA Langley	Flight deck
4,5,6	Flight simulators (MD11, Advanced Cab, B747-400)	NASA Ames	Flight deck
3,4,5	PAS	NASA Ames	Pseudo aircraft
3,4,5	ASAC	NASA Ames	Integrated suite of models and databases
1,2,3,4,5,6	CVSRF	NASA Ames	Flight deck simulator
3,4,5,6	CTAS Laboratory:	NASA Ames	En route and terminal domain with conflict probe
2,3	Stone Soup Simulator	NASA Ames	Flight deck
1,2,3,4,5,6	VAST	NASA Ames	Gate-to-gate capability
2,3,4	VLAB	NASA Ames	Virtual Laboratory
2,3,4,5,6	ARIMM	FAA WJHTC	Modeling and Simulation tool; Suite for gate-to-gate capability
2,3,4,5,6	RDHFL	FAA WJHTC/RDHFL	Overall simulation environment
3,4,5,6	DSR En Route Host Laboratory	FAA WJHTC	Laboratory
3,4,5,6	STARS Laboratory	FAA WJHTC	Laboratory
3,4,5,6	ARTS Laboratory	FAA WJHTC	Laboratory
3,4,5,6	TGF	FAA WJHTC	Modeling and Simulation support
2,3,4	ATC Coach	FAA WJHTC/RDHFL	En route and terminal domain
2,3,4	SATORI	FAA WJHTC	AT replay
1,2,3,4,5,6	EI^2F	FAA WJHTC	En route domain
3,4,5,6	DYSIM	FAA ARTCC	En route domain
3,4,5	ODS Tool Box	FAA WJHTC/RDHFL	Prototyping display
2,3,4,5, 6	DESREE	FAA WJHTC/RDHFL	En route and terminal domain

A.5 SIMULATOR AND SIMULATION FIDELITY

Webster's dictionary defines the term fidelity as a quality or state of being faithful. A simulator represents an actual system. Simulator fidelity refers to how well that simulator represents the actual system. For example, various flight simulators are available in the commercial market. Among other attributes, they differ in their representation of flight dynamics, controls, display and avionics models. These simulators represent an aircraft in some fashion. Their representation accuracy and details differ from each other.

A.5.1 FIDELITY TYPES

Simulator fidelity can be divided into functional and physical aspects. Functional fidelity refers to the functions and capabilities of a simulator, for example, a fuel-burn model of a cockpit simulator. The functional fidelity is very important for fast-time simulation studies. Physical fidelity refers to the appearance and human-machine interfaces of a simulator as compared to their counterparts of the real-world operational system that is being simulated. The physical fidelity is particularly important in the human-in-the-loop (HITL) simulation studies. The HITL simulation studies involve human participants interacting with the systems or simulators. Therefore, participant fidelity needs to be considered as well. If the study participants do not accurately represent the study population, the results may be biased. The use of statistical sampling procedures is related to participant fidelity. For example, the study participants should closely represent the experience, age, gender, and other important population characteristics.

The simulator and simulation fidelity is very important for the validity of simulation results. Therefore, experimenters, managers and sponsors are often interested in selecting a simulator that offers adequate fidelity at an affordable cost. Typically, the higher the fidelity, the higher the cost of a simulator (e.g., either to rent or to buy). Therefore, a fidelity-cost tradeoff analysis is useful for selecting a simulator. Fidelity of a simulator is also crucial in training studies. Clearly, the higher the simulator fidelity the more realistic the training is.

A.5.2 IMPORTANCE OF FIDELITY ASSESSMENT

Quantification of simulation fidelity is not very easy, although simulator fidelity assessment is very important. Additionally, standard methods for calculating simulator fidelity do not exist. Recently, various researchers have attempted to develop methods to quantify simulator and simulation fidelity. Experimenters, managers and sponsors are often interested in a metric of simulator fidelity and are not satisfied with gross classification of high, medium, and low fidelity simulator. To date, a standard fidelity quantification technique does not exist. However, the following section presents a few techniques that are used in the industry.

A.6 FIDELITY ASSESSMENT METHODS

A.6.1 FIDELITY BASED ON GENERAL CLASSIFICATION

The conventional method of fidelity assessment is to classify the fidelity of a simulator as low, medium or high. This classification is based on presence or absence of certain simulator attributes (e.g., avionics, range of motions, etc.). Other approach is to classify simulator fidelity as Class A, Class B, Class C, etc. based on its characteristics and attributes. A simulator possessing the highest fidelity classification is typically certified for training exercises. This method is very easy to apply and understand. However, this method disregards the fact that not all studies require the highest fidelity in all attributes. For example, a study focusing on display layout in the cockpit will require accurate representation of display size, location and other details. However, six degrees of freedom and more accurate engine models may not be required.

A.6.2 FIDELITY BASED ON ADEQUACY OF A SIMULATOR

Often times, researchers are interested in determining if an available simulator offers adequate fidelity to meet the objectives of a simulation. The adequacy of a simulator can be determined as follows:

- *Identification of the attributes that are important to the study objectives*. For example, if it is an air traffic control display simulator, it may be important to realistically represent the rate of aircraft turn, rate of climb and descend, aircraft data symbol, etc.
- *Determination of the importance of these attributes in a simulation on a 1-7 rating scale.* The importance rating can be received from users or subject matter experts. A rating of 1 on the scale means very low importance, 4 indicates moderate importance, and 7 indicates very high importance. The importance ratings of a simulation attribute may vary from one study to another depending on the study objectives.
- *Determination of the performance of these attributes of a simulator in a test on a 1-7 scale.* In order to assess the performance, a representative test must be conducted. This test involves a study scenario. For example, an air traffic control display will involve display of aircraft operating in certain airspace. The performance rating can be received from users or subject matter experts. A rating of 1 means very low importance, 4 on a rating-scale indicates moderate importance, and 7 indicates very high importance.
- *Developing an importance-performance matrix, with importance is in columns and performance is in rows*. Based on the ratings, the attributes are filled in the matrix. An example is shown in Table A-3 (Kopardekar et al., 1997).

Table A-3. Importance-Performance Matrix for Fidelity Assessment

	Importance Rating						
Performance Rating	**1 Very Low Importance**	**2**	**3**	**4 Moderate Importance**	**5**	**6**	**7 Very High Importance**
1 – Very Low Performance							*Climb rates*
2 –							
3 –							
4 – Moderate Performance				*Turn rates*			
5 –							
6 –							
7 – Very High Performance							*Aircraft data symbol*

Table A-3 shows that the example simulator has high performance and high importance for the attribute of *aircraft data symbol* presentation. It has low performance, but very high importance for *climb rate* representation. This will indicate that the simulator in question is not adequate for the study. Typically, a simulator will be adequate if all important attributes (5 or above rating on importance scale) have good performance (five or above on performance scale). If high importance is desired but low performance is experienced (three or below rating), the simulator is not adequate for the application. Low performance ratings are accepted if they receive low importance ratings as well.

A.6.3 FIDELITY BASED ON QUANTITATIVE APPROACH

Fidelity of a simulator depends on the application under investigation. For example, consider two cockpit simulators. The first simulator has six degrees of freedom and the second simulator has no degrees of freedom. However, both simulators have the same avionics and the same cockpit displays. These two simulators will certainly have different fidelity for a motion sickness assessment study but will have the same fidelity for display layout assessment study. Clearly, the fidelity of a simulator depends on the attributes of a simulator that are useful to the simulation objectives. A simulator attribute, which perfectly represents the real-world operational attribute (e.g., six degrees of freedom) but is not required for a specific simulation application, does not contribute to the fidelity.

Often, experimenters have to select a simulator among available options. Each simulator may be different in their fidelity and cost. Therefore, a systematic method is required for the assessment of fidelity. The following approach can be used to determine simulator fidelity that represents the same system. The objective is to select a simulator among available simulators. For example, consider two flight simulators with the goal of selecting one of them for a study. Any number of simulators can be considered. Kopardekar developed the following method in late 1990s. The following steps describe the fidelity assessment process (Nouragas, Watts, Kopardekar, and Richards, 1997; Kopardekar, 1999):

Step 1 - Identify candidate simulators.

In this example, we assumed that two simulators are available and only one is required. However, any number of simulators can be considered.

Step 2 - Identify attribute values for each candidate simulator.

In this step, the required simulator attributes, its associated values and its real-world operational counterpart are identified. All attributes necessary to achieve the objectives are identified and the attribute values are documented. Table A-4 provides an example. Only two attributes are considered in this example. However, any number of attributes can be considered.

Table A-4. Simulator Attributes

Example Attribute	Simulator 1	Simulator 2	Real-World Operational System
Functional Attributes			
Lateral position accuracy (ft)	300	200	275
Physical Attributes			
Character Size (cm)	1	2	2

In cases where a real-world operational system may not exist but may be under development or at a prototype stage, then the attribute values can be derived from the requirements document.

Step 3 - Normalize simulator attribute values.

In order to compare attribute values using a uniform scale, attribute values need to be normalized. Otherwise, higher attribute values may dominate the lower values (e.g., the lateral accuracy is in hundreds and the character sizes are below 10 mm). The following sub-steps identify the normalization process.

Step 3.1 - Subtract real-world operational attribute from simulator attribute values.

In this step, the real-world operational system's attribute values are subtracted from the candidate simulator attributes. Only absolute values are considered (if the result is negative, the sign is neglected).

If a good performance of an attribute is indicated by a small value (e.g., lateral accuracy), then resulting negative value indicates that the simulator performs better than the real-world operational system. In such cases, the simulator attribute is considered as over-modeled (OM). Conversely, the positive subtraction value indicates that the simulator is not performing as well as the real-world operational system. In such cases, the simulator attribute is considered as under-modeled (UM).

However, if a good performance of an attribute is indicated by a large value (e.g., reliability), then a resulting negative value indicates that the simulator is not performing as well as the real-world operational system. In such cases, the simulator attribute is considered UM. Conversely, a positive subtraction result indicates that the simulator is performing better that the real-world operational system for that attribute. Thus, that simulation attribute is considered to be OM.

If subtraction of the real-world operational attribute value from the simulator attribute value results in zero difference, the simulator performance is identical to that of its real-world operational counterpart for the attribute in question. In such cases, the simulation attribute is considered as perfect (P). These calculations are indicated in Table A-5.

Table A-5. Simulator Attribute Status

Example Attribute	Simulator 1	Simulator 2	Real-World Operational System
Functional Attributes			
Lateral position accuracy (ft)	300 - 275= 25 (UM)	200 - 275 = 75 (OM)	275
Physical Attributes			
Character Size (cm)	1 - 2 = 1 (UM)	2 - 2 = 0 (P)	2

The UM or OM status is important in selecting a simulator. Two simulators may have the same fidelity on a certain attribute but one may be UM and the other may be OM. The experimenters should select a simulator based on study objectives and importance of UM and OM for that application.

Step 3.2 - Divide the subtraction result of an attribute by the range value of an attribute.

In this step, each simulator's subtraction result is divided by the range (maximum - minimum) of a particular attribute. Table A-6 provides these calculations.

Table A-6. Simulator Attribute Normalization

Example Attribute	Simulator 1	Simulator 2	Real-World Operational System
Functional Attributes			
Lateral position accuracy (ft)	25/(300-100) =0.125	75/(300-100) = 0.375	275
Physical Attributes			
Character Size (cm)	1/(2-1) = 1	0/(2-1) = 0	2

Steps 3.1 and 3.2 together normalize attribute values and therefore all resulting attribute values are in the range of 0 to 1, providing a uniform scale for comparisons. These normalized attribute values represent how well each simulator attribute represent the real-world system attributes (in other words, attribute-level fidelity for each simulator).

Step 4 - Determine weights for each attribute.

In a simulation, some attributes may be more important than others for meeting the study objectives. To determine their weights, a 1-7 rating scale is used. Users, subject matter experts, or experimenters provide the ratings. If the ratings are obtained from more than one person, then arithmetic average, median, or geometric mean can be considered as a measure of central tendency. Table A-7 provides the weights assuming that the ratings are obtained from one individual.

Table A-7. Attribute-Weights Determination

Example Attribute	Simulator 1	Simulator 2	Rating on 1-7	Weight
Functional Attributes				
Lateral position accuracy (ft)	0.125	0.375	7	7/12 = 0.583
Physical Attributes				
Character Size (cm)	1	0	5	5/12 = 0.416
			Total = 12	

If all attributes are equally important then they all will receive the same weight.

Step 5 - Compute weighted fidelity for simulator attributes.

At this step, for each attribute, a weighted fidelity can be computed by multiplying attribute weight computed in the Step 4 and the normalized attribute fidelity computed in Step 3.

Table A-8 describes these calculations.

Table A-8. Weighted Attribute Fidelity Computation

Example Attribute	Simulator 1	Simulator 2
Functional Attributes		
Lateral position accuracy (ft)	0.125*0.583 = 0.072	0.375*0.583 = 0.2186
Physical Attributes		
Character Size (cm)	1*0.416 = 0.416	0*0.416 = 0

Step 6 - Calculate simulator fidelity.

Once the importance-weighted attribute fidelity values are computed, the simulator fidelity can be computed by sum of all importance-weighted attribute fidelity values for a simulator. Table A-9 shows these calculations.

Table A-9. Simulator Fidelity Computation

Example Attribute	Simulator 1	Simulator 2
Functional Attributes		
Lateral position accuracy (ft)	0.125*0.583 = 0.072	0.375*0.583 = 0.2186
Physical Attributes		
Character Size (cm)	1*0.416 = 0.416	0*0.416 = 0
Total Simulator Fidelity	0.488	0.218

It should be noted that since the real-world operational attribute values were subtracted from simulator attribute values, the closer the fidelity values to zero, the higher the fidelity. Therefore, Simulator 2 (overall fidelity 0.218) offers the maximum fidelity. Zero value indicates the perfect representation and the highest possible fidelity.

A.6.4 FIDELITY-COST TRADE-OFF

At this point, if desired, a fidelity-cost tradeoff analysis can be performed if the costs of operation of these simulators are known.

To illustrate, Table A-10 contains the hypothetical results of calculations for two simulators capable of satisfying the needs of a particular simulation element. As shown, Simulator 2, with a value of 0.218, has the highest fidelity when adjusted for importance. However, it will cost $1000 to use it. Simulator 1 can be used for $700 with the lower fidelity.

Table A-10. Fidelity and Cost Table

	Simulator 1	Simulator 2
Simulator Fidelity	0.488	0.218
Cost	$700	$1000

Simulators 1 and 2 would then be compared to determine if a reduction in fidelity is acceptable to achieve the 30% cost savings offered by choosing the Simulator 2. Researchers and sponsors can then make informed decisions on simulator choices.

The advantage of this method is that it quantifies fidelity and identifies attributes that are over-modeled and under-modeled. However, as the number of simulator attributes increase the computation becomes lengthy. The method also requires that the analyst identify all attribute values.

This Page Intentionally Left Blank

REFERENCES

Corker, K. M., & Smith, B. (1993). An architecture and model for cognitive engineering simulation analysis: Application to advanced aviation analysis. Presented at *AIAA Conference on Computing in Aerospace,* San Diego, CA.

Federal Aviation Administration. (1998). *Operational Concept Validation Process* (ACT-540 report). Atlantic City, NJ: Author.

Kopardekar, P. (1999). Simulation Fidelity. In Mital (Ed.), *Encyclopedia of Industrial Ergonomics.* Cincinnati, OH: University of Cincinnati. [CD-ROM].

Kopardekar, P., DiMeo, & Stahl, D. (1997). *DYSIM fidelity evaluation for conducting GOERS study* (ACT-540 report). Atlantic City, NJ: DOT/FAA Technical Center.

NASA Ames Simulator RTO 58. (2001). Contract DTFA01-88-C00042, pp 13.

Nouragas, P., Watts, N., Kopardekar, P., & Richards, J. (1997). Fidelity Assessment in Aviation Related Simulation Applications. *Simulation and Interoperability Workshop.* Simulation, Interoperability and Standards Organization (SISO).

O'Briant, E. (2001). The Next Big Thing. Institute of Industrial Engineering. *Solutions Magazine*, pp. 24-29.

Odoni, A., Bowman, J., Dalahaye, D., Deyst, J, Feron, E., Hansman, J., Khan, K., Kuchar, K., Pujet, N. & Simpson, R. (1997). *Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts* (MIT Report for NASA AATT). Moffett Field, CA: NASA Ames Research Center.

Schwartz, A. & Kopardekar, P. (2000). *Evaluation of RAMS workload module* (ACT-540 report). Atlantic City, NJ: DOT/FAA Technical Center.

This Page Intentionally Left Blank

BIBLIOGRAPHY

Bilimoria, K., Sridhar, B., Chatterji, G., Sheth, K., & Grabbe, S., (2000). *FACET: Future ATM Concepts Evaluation Tool*. Free Flight DAG-TM Workshop, NASA Ames Research Center, 24 May 2000.

DELAYS (1996). Available: http://web.mit.edu/aeroastro/www/labs/AATT/reviews/delays.html

Hook, M. (1997) Available: http://www.objectplus.co.uk/pumainfo.htm

Lee, D. A., Nelson, C., & Shapiro, G, (1998). *The Aviation System Analysis Capability Airport Capacity and Delay Models*. (NASA/CR-1998-207659), McLean, VA: Logistics Management Institute.

Roberts, E., Villani, J. A., Osman, M., Godso, D., King, B., & Ricciardi M., (1998). *Aviation System Analysis Capability Executive Assistant Design.* (NASA/CR-1998-207679). McLean, VA: Logistics Management Institute.

The Assembly of a Generic Airborne ATM Platform (AGAAP) Project (2000). Available: http://www.dera.gov.uk/html/aerospace/the_assembly_ofa_generic_airborne_atm_platform_agaap_project.htm

Wingrove, E. R. III, Gaier, E. M., & Santmire, T. E., (1998). *The ASAC Air Carrier Investment Model (Third Generation).* (NASA/CR-1998-207656). McLean, VA: Logistics Management Institute.

This Page Intentionally Left Blank

ACRONYM LIST

4-D	Four Dimensional; speed, distance, altitude, time
AATT	Advanced Air Transportation Technology
ACIM	Airspace Simulation
ACM	Airfield Capacity Model
AGAAP	Assembly of a Generic Airborne ATM Platform
AIRMM	Aviation Integrated Reasoning Modeling Matrix
AND	Approximate Network Delays
AOC	Airline Operations Center
AOP	Autonomous Operations Planner
ARC2000	Automatic Radar Control for the years beyond 2000
ARIMM	Aviation Integrated Reasoning Modeling Matrix
ARTCC	Air Route Traffic Control Center
ARTS	Arrival Route Terminal System
ASAC	Aviation System Analysis Capability
ASIM	Airspace Simulation
AT	Air Traffic
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATOL	Air Traffic Operations Laboratory
ATSP	Air Traffic Service Provider
BDT	Banc De Test
CAA	Civil Aviation Authority
CAASD	Center for Advanced Aviation System Development

CDR	Coded Departure Route
CDTI	Cockpit Display of Traffic Information
CE	Concept Element
CENA	Centre d'Études De la Navigation Aerienne
CTAS	Center TRACON Automation System
CVSRF	Crew-Vehicle Systems Research Facility
DAG-TM	Distributed Air-Ground Traffic Management
DERA	Defense Evaluation and Research Agency
DESREE	Distributed Environment for Simulation, Rapid Engineering, and Experimentation
DRA	Defense Research Agency
DSR	Display System Replacement
DST	Decision Support Tool
DYSIM	Dynamic Simulation Laboratory
EI^2F	En Route Integration and Interoperability Facility
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FACET	Future ATM Concepts Evaluation Tool
FD	Flight Deck
FFC	Future Flight Central
FY	Fiscal Year
GUI	Graphical User Interface
HERMES	Heuristic Runway Movement Event Simulator
HIPS	Highly interactive problem solver
HITL	Human-in-the-loop
HLA	High Level Architecture
HMI	Human machine interface

IMC	Instrument Meteorological Conditions
INM	Integrated Noise Model
Ldn	Day-Night Average Sound Level
Leq	Equivalent Sound Level
LMI	Logistics Management Institute
MIDAS	Man-Machine Integration, Design, and Analysis System
MIT	Massachusetts Institute of Technology
NARIM	National Airspace Resource Investment Model
NARSIM	NLR ATC Research Simulator
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASPAC	National Airspace System Performance Capability
NATS	National Air Traffic Services
NAVAIDS	Navigational Aids
NEF	Noise Contour Levels
NLR	National Aerospace Laboratory
ODS	Orthogon Display System
OM	Over modeled
P	Perfect
PAS	Pseudo Aircraft Simulator
PUMA	Performance and Usability Modeling in ATM
RAMS	Reorganized ATC Mathematical System
RATSG	Robust Air Traffic Simulation Generator
RCS	Reconfigurable Cockpit Simulator
RDHFL	Research Development and Human Factors Laboratory
RT	Real Time

RTA	Required Time of Arrival
SAR	Synthetic Aperture Radar
SATORI	Systematic Air Traffic Operations Research Initiative
SDAT	Sector Design Analysis Tool
STARS	Standard Terminal Automation Replacement System
SUA	Special Use Airspace
TA	Time Above Threshold of Weighted Sound
TAAM	Total Airspace & Airport Modeler
TCAS	Traffic Alert and Collision Avoidance System
TFM	Traffic Flow Management
TGF	Target Generation Facility
TOPAZ	Traffic Organization of Perturbation Analyzer
TRACON	Terminal Radar Approach Control
TRL	Technology Readiness Level
UM	Under modeled
VAST	Virtual Airspace Simulation Technology
VLAB	Virtual Laboratory
VMC	Visual Meteorological Conditions
WJHTC	William J. Hughes Technical Center (NJ)
VSCS	Voice Switching Control System